Alexandria Engineering Journal (2015) 54, 565–575

HOSTED BY

Alexandria University

Alexandria Engineering Journal

www.elsevier.com/locate/aej
www.sciencedirect.com

ORIGINAL ARTICLE

Self-curing concrete types; water retention and durability

Magda I. Mousa [a,*], Mohamed G. Mahdy [a], Ahmed H. Abdel-Reheem [a], Akram Z. Yehia [b]

[a] *Structural Engineering Department, Faculty of Eng. El-Mansoura University, El-Mansoura, Egypt*
[b] *Civil Engineer, Ministry of Water Resources and Irrigation, El-Mansoura, Egypt*

Received 5 July 2014; revised 12 March 2015; accepted 31 March 2015
Available online 23 April 2015

KEYWORDS

Self-curing concrete;
Leca;
Polyethylene-glycol;
Silica fume;
Water retention;
Durability

Abstract Internal curing of concrete by the use of pre-saturated lightweight aggregates or polyethylene-glycol is well established method of counteracting self-desiccation and autogenous shrinkage.

This study was carried out to compare among concretes without or with silica fume (SF) along with chemical type of shrinkage reducing admixture, polyethylene-glycol (Ch), and leca as self-curing agents for water retention even at elevated temperature (50 °C) and their durability. The cement content of 400 kg/m^3, silica fume of 15% by weight of cement, polyethylene-glycol of 2% by weight of cement, pre-saturated lightweight aggregate (leca) 15% by volume of sand and water with Ch/binder ratio of 0.4 were selected in this study. Some of the physical and mechanical properties were determined periodically up to 28 days in case of exposure to air curing in temperature of (25 °C) and (50 °C) while up to 6 months of exposure to 5% of carbon dioxide and wet/dry cycles in 8% of sodium chloride for durability study. The concrete mass loss and the volumetric water absorption were measured, to evaluate the water retention of the investigated concretes. Silica fume concrete either without or with Ch gave the best results under all curing regimes; significant water retention and good durability properties.

1. Introduction

The recent trend in concrete technology toward the so-called high-performance, or low water/solid binder mass ratio (w/b), concretes encountered some problems. One of the major problems with such a mixture is its increased tendency to undergo early-age cracking. While this cracking may or may not compromise the (higher) compressive strength of these concretes, it likely does compromise their long-term durability. The phenomenon of early-age cracking is complex and depends on thermal effects, autogenous strains and stresses, drying, stress relaxation, and structural detailing and execution. In concretes with low w/binder ratio, a major contributor to early-age cracking can be the autogenous shrinkage induced by the self-desiccation that occurs during hydration under sealed or partially saturated conditions [1]. As the cementitious

* Corresponding author.

Peer review under responsibility of Faculty of Engineering, Alexandria University.

http://dx.doi.org/10.1016/j.aej.2015.03.027
1110-0168

materials hydrate under sealed conditions, empty porosity is created within the "set" microstructure, because the hydration products occupy less volume than the reacting materials. The water menisci created by these empty pores in turn induce compressive stresses in the three-dimensional microstructure. The magnitude of these stresses is influenced by both the surface tension of the pore solution [2] and the meniscus radius of the largest water-filled pore within the microstructure [1]. Concrete incorporating self-curing agents will represent a new trend in the concrete construction in the new millennium, due to the increased use of high-performance concrete. Several techniques may, potentially, be used for incorporation of internal curing water in concrete [3]. Several researchers have proposed the use of saturated light weight aggregates to provide "internal" curing for concrete [4–9]. On the other hand, other researchers used poly-glycol products in concrete mixes as self-curing agent [10,11].

In this paper, three engineering methods for reducing autogenous stresses and strains by internal water supply for internal curing are compared under air-curing regime in normal temperature (25 °C) and high temperature (50 °C) and are examined for their effect on the concrete resistance to carbon dioxide (5%) and wet/dry cycles in saline water (8% sodium chloride). These three methods are the replacement of sand by saturated low-density fine aggregates (leca) which provides the cement paste by store water in saturated Leca particles [12] thereby mitigate the effects of self-desiccation in low w/b concrete mixture [6], adding polyethylene-glycol by weight of cement which reduces the water evaporation from concrete, and hence increase the water retention capacity of the concrete [13], and the addition of silica fume by weight of cement which retains water and causes continuation of the cement hydration and to conversion of the calcium hydroxide, which tends to form on the surface of aggregate particles into calcium silicate hydrate (C-S-H) and strengthening the aggregate matrix transition zone, which becomes less porous and more compact [3,14,15].

2. Scope and objectives

A comprehensive experimental investigation has been undertaken to study the effects of self-curing agents such as pre-soaked (in water) lightweight aggregate (leca), polyethylene-glycol and the addition of SF on the mechanical and non-mechanical properties of concrete and its durability. The considered concrete properties are compressive, tensile strength, volumetric water absorption, Ph value and mass loss. The test program was performed on concretes containing cement content (400 kg/m^3), water (including Ch)-cement ratio (0.4) cured in air (25 °C) and elevated temperature (50 °C). The research aimed to examine the resistance of the aforementioned concretes to carbon dioxide (5%) and wet/dry cycles in saline water (8% sodium chloride). Special attention was given to the enhancement in self-curing concrete properties cured in normal (25 °C) and elevated temperature (50 °C), as well as its durability to carbon dioxide and wet/dry cycles in saline water as affected by the type and doses of self-curing agent (SCUA) along with the addition of silica fume.

3. Experimental program

3.1. Material and mix proportion

The ordinary Portland cement and silica fume with chemical composition illustrated in Table 1, siliceous sand as a fine aggregate with fineness modulus of 2.79, and gravel coarse aggregate of nominal maximum size (20 mm) from Suez quarry were used throughout the program for producing concrete. The superplasticizer (SP) used was of the sulphated naphthalene formaldehyde condensate type. The superplasticizer dosage was adjusted to produce concretes with the same slump of 120 ± 10 mm and do not show visual signs of segregation during the normal casting of concrete in the molds. Leca which is brand name for an expanded clay clinker and burned in a rotary kiln at approximately 1200 °C was used as self-curing agent of light weight aggregate type, while polyethylene-glycol characteristics as produced by the manufacturer indicated in Table 2 was used as self-curing agent of chemical type. The proportions of concrete batches are given in Table 3.

3.2. Experimental procedure

Mixing of concrete components was achieved by using a horizontal mixer. The Leca was oven-dried at 105 °C for 24 h, air cooled and then submerged in water for 24 h before mixing. All the dry constituents were placed in the mixer and mixed for 2 min to ensure uniformity of the mix. Half of the mixing water was added gradually during mixing and followed by the

Table 1 Chemical composition of Portland cement and silica fume.

Chemical composition (%)	Portland cement	Silica fume
Loss on ignition	1.36	1.0
SiO_2	19.49	95
Al_2O_3	7.36	0.4
Fe_2O_3	2.68	0.6
CaO	62.51	0.2
MgO	3.7	0.4
SO_3	2.4	0.3
Specific weight (g/cm^3)	3.12	2.2
Specific surface (cm^2/g)	3000	150,000
Mineralogical components (%)		
C3S	37.17	–
C2S	33.65	–
C3A	11.73	–
C4AF	8.15	–

Table 2 Characteristics of polyethylene-glycol.

Type	Molecular weight	Maximum solubility at 20 °C (mass fraction%)	Functional group	
			Hydroxyl	Ether
Synthetic	200	100	Yes	Yes

Table 3 Composition of concretes (kg/m^3).

Concrete mix	Cement (C)	Water (W)	Super-plasticizer (SP)	Silica fume (SF)	Self-curing agent (SCUA)		Gravel (20 mm)	Sand	W + Ch/C + SF
					Ch.	Leca			
M1 (Ref.)	400	160	4	–	–	–	1189	640	0.4
M2 (15% SF)		184	2.8	60(15%)	–	–	1102	592	0.4
M3 (2% Ch.)		152	4	–	8(2%)	–	1189	640	0.4
M4 (15% Leca)		160	4	–	–	37(15%)	1190	544	0.4
M5 (SF + Ch)		175	2.8	60(15%)	9.2(2%)	–	1102	592	0.4
M6 (SF + Leca)		184	2.8	60(15%)	–	34(15%)	1096	500	0.4

remaining water with SP. Finally, in the case of SCUC, self-curing agent such as Polyethylene-glycol or saturated light weight aggregate (leca) was added gradually during mixing. Mixing of all ingredients continued for a period of 2 min. The content of SP was adjusted for each mix to ensure that no segregation would occur and to achieve the required workability. After mixing, the mixture was cast into $10 \times 10 \times 10$ cm cubic molds and cylindrical molds with internal diameter 10 cm and height 20 cm at three equal layers, each layer was compacted by hand tamping and on mechanical vibrator table. After the molds had been filled of concrete, the surface of concrete in molds was leveled and they were kept in the laboratory conditions for 24 h while the surfaces of molds were covered by plastic sheets. Then, the specimens were demolded and exposed to four curing regimes; the first kept in air (25 °C) with relative humidity environment of about 65% for 28 days, the second kept in air (50 °C) for 28 days, the third exposed to carbon dioxide (5%) for 6 months, in which it was renewed periodically every 30 days and the fourth exposed to wet/dry cycles in saline water (8% sodium chloride) for 6 months where each cycle equals to two weeks. Compressive, tensile strength (indirect test), Ph values, volumetric water absorption (VWA) and the depth of saline water penetration were carried out on cubic specimens. The VWA was calculated as the difference between saturated dry and dry masses of specimens. While, the mass loss was performed on Polypropylene containers of 1.57 L with internal diameter 10 cm and height 20 cm, filled with concrete. The weight of the containers was measured after casting and at several intervals to determine the mass loss with time. Saline water (Na Cl) depth was determined by cutting the cubes perpendicular to its cast surface and spray silver nitrate (Ag NO_3) solution on the inner surface of the freshly cut section, wetted concrete turns to white color. The solution depth was determined as the average of 10 measurements.

4. Results and discussions

4.1. Compressive strength

Fig. 1 reveals that, the compressive strength of all concrete mixes (self-curing and conventional concretes) increased gradually with time under air curing (25 °C). Compressive strength systematically increases when self-curing agents used in concrete, which may be attributed to the continuation of the hydration process, which leads to, lower voids and pores, and greater bond force between the cement paste and aggregates as stated by Bentz et al., Cusson et al. and Jensen et al. [8,16–18]. Silica fume concretes show significant higher in

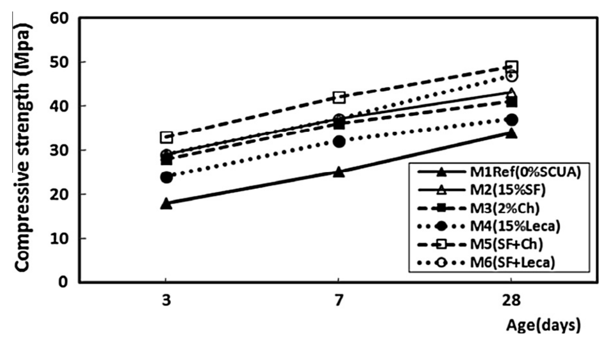

Figure 1 Effect of self-curing agent type on compressive of concrete strength (air-curing at 25 °C).

strength during the experiment compared with their corresponding concretes without SF. In general, at 28 days, self-curing concretes containing 15% silica fume (SF), 2% Ch and 15% leca gave higher compressive strength by about 26.5%, 20.6% and 8.8%, respectively, compared with the reference concrete (M1Ref), 0.0% SCUA.

For the concrete series cured in elevated temperature (50 °C), reference concrete gives higher strength at early age compared with self-curing concretes, which may be attributed to the acceleration of cement hydration, beyond that, gradual reduction of strength gain was observed up to 28 days as shown in Fig. 2. On the other hand, strength of silica fume and self-curing concretes increased with time up to 28 days and gave higher strength values than reference concrete. After 28 days self-curing concretes with 15% silica fume, 2% Ch and 15% leca exhibited higher compressive strength by about 21.6%, 16.2% and 8.1%, respectively, compared with conventional concrete.

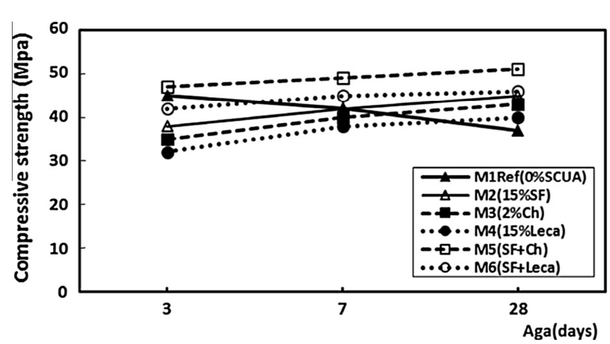

Figure 2 Effect of self-curing agent type on compressive strength of concrete (air-curing at 50 °C).

Although the elevated temperature (50 °C) caused gradual reduction in the compressive strength of the reference concrete, the value of strength at 28 days was higher compared with normal temperature (8.8% increase). On the other hand, the elevated temperature increased the strength of self-curing concretes during the experiment compared with normal temperature, which may be attributed to the acceleration of cement hydration and therefore the compressive strength was increased compared with their corresponding concrete cured in normal temperature (25 °C), (Table 4).

Upon comparing the results of the self-curing concretes with and without SF, the concrete containing 15% silica fume with 2% Ch recorded the highest increase in the compressive strength by about 44%, 37.8% for concrete cured in normal and elevated temperature, respectively, relative to the conventional concrete at 28 days, (Table 4).

4.2. Tensile strength

The incorporation of self-curing agents into concrete mixtures provides internal curing for the concrete and thus allowing a continuous hydration, which results in an improvement in the tensile strength of the concrete as shown in Fig. 3. The tensile strength of all studied concretes increased gradually with time under air curing (25 °C). Concrete with silica fume showed the highest strength during the experiment followed by concrete with Ch, leca and conventional concrete. At 28 days concrete with 15% silica fume and self-curing concretes with, 2% Ch and 15% leca gave higher tensile strength by about 29.8%, 14.3% and 9.1%, respectively, compared with conventional concrete.

Fig. 4 illustrates that the tensile strength of the reference concrete is higher at early age compared with the self-curing concrete when exposed to high temperature (50 °C); beyond that, continuous reduction is observed up to 28 days. On the

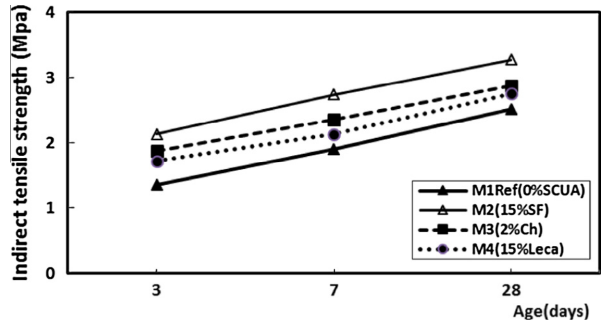

Figure 3 Effect of self-curing agent type on indirect tensile strength of concrete (air-curing at 25 °C).

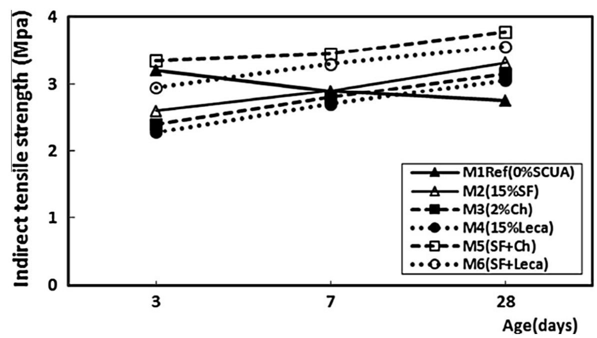

Figure 4 Effect of self-curing agent type on indirect tensile strength of concrete (air-curing at 50 °C).

Table 4 Comparison between normal (25 °C) and elevated temp (50 °C) on different concrete properties at 28 days age.

Concrete mix	Considered property									
	Compressive strength (MPa)					Indirect tensile strength (MPa)				
	Curing at 25 °C	Vari.[a] %	Curing at 50 °C	Vari.[b] %	Vari.[c] %	Curing at 25 °C	Vari.[a] %	Curing at 50 °C	Varia.[b] %	Vari.[c] %
M1 (Ref.)	34	0.0	37	0.0	+8.8	2.52	0.0	2.75	0.0	+9.1
M2 (15% SF.)	43	+26.5	45	+21.6	+4.7	3.27	+29.8	3.32	+20.7	+1.5
M3 (2% Ch.)	41	+20.6	43	+16.2	+4.9	2.88	+14.3	3.15	+14.6	+9.4
M4 (15% leca)	37	+8.8	40	+8.1	+8.1	2.75	+9.13	3.06	+11.3	+11.3
M5 (SF + Ch)	49	+44.1	51	+37.8	+4.1	–	–	3.78	+37.5	–
M6 (SF + Leca)	47	+38.2	46	+24.3	−2.1	–	–	3.56	+29.5	–
Concrete mix	Considered property									
	V.W.A. (g/L)					Mass Loss (g)				
	Air curing at 25 °C	Vari.[a] %	Air curing at 50 °C	Vari.[b] %	Vari.[c] %	Air curing at 25 °C	Vari.[a] %	Air curing at 50 °C	Varia.[b] %	Vari.[c] %
M1 (Ref.)	57	0.0	62	0.0	+8.8	62	0.0	138	0.0	+123
M2 (15% SF.)	40	−29.8	45	−27.4	+12.5	48	−22.6	110	−20.3	+129
M3 (2% Ch.)	49	−14.0	55	−11.3	+12.3	50	−19.4	115	−16.7	+130
M4 (15% leca)	55	−3.5	60	−3.2	+9.1	59	−4.8	122	−11.6	+107
M5 (SF + Ch)	36	−36.8	40	−35.5	+11.11	–	–	102	−26.1	–
M6 (SF + Leca)	42	−26.3	48	−22.6	+14.29	–	–	110	−20.3	–

[a] The variation in the values of the considered property (at 25 °C) compared to the value of M1 (Ref.).
[b] The variation in the values of the considered property (at 50 °C) compared to the value of M1 (Ref.).
[c] The variation in the values of the considered property at 50 °C compared to the values at 25 °C.

other hand, the tensile strength of SF and self-curing concretes increased with time up to 28 days and gave higher values of strength than reference concrete. Concretes with 15% silica fume and 2% Ch or 15% leca (M5, M6) gave higher tensile strength by about 37.5%, 29.5% at 28 days, respectively; relative to the reference concrete (M1).

The test results indicated that, although the reference concrete lost part from its tensile strength during 28 days when exposed to high temperature (50 °C), the 28 days tensile strength value still higher compared with reference concrete in normal temperature (Fig. 3). Add to that, the higher temperature improved the tensile strength of self-curing concretes during the experiment compared with their corresponding concretes in normal temperature at 28 days as shown in Table 4.

4.3. Volumetric water absorption

It can be noted from Fig. 5 that the volumetric water absorption of all concrete mixes (self-curing and conventional concretes) decreased gradually with time under air curing. While, the self-curing concrete recorded higher reduction in the volumetric water absorption (VWA), which may be attributed to a better water retention and hence more hydration process of cement [19,20], which produces less porous concrete. At 28 days the concretes containing 15% silica fume either without SCUA (M2) or with 2% Ch, 15% leca have reduced their volumetric water absorption by about 29.8%, 36.8% and 26.3%, respectively, compared with conventional concrete.

It is well known that, the addition of self-curing agents into concrete mixtures causes better water retention capacity in concrete even at high temperature [13] and hence producing a less porous and more compact concrete than conventional concrete, which seems obvious in Fig. 6. Comparing the volumetric water absorption of concretes containing SF and concretes without SF shows a significant reduction in VWA after 28 days due to SF addition, the highest reduction was by about 27.4% and 35.5% for concretes with 15% SF (M2) and with 15% SF + 2% Ch (M5), respectively.

A comparison between the results of VWA of all concrete mixes cured in normal (25 °C) and elevated temperature (50 °C) are shown in Table 4. After 28 days, the studied concretes without and with SCUA gave higher volumetric water absorption when exposed to elevated temperature compared with normal temperature.

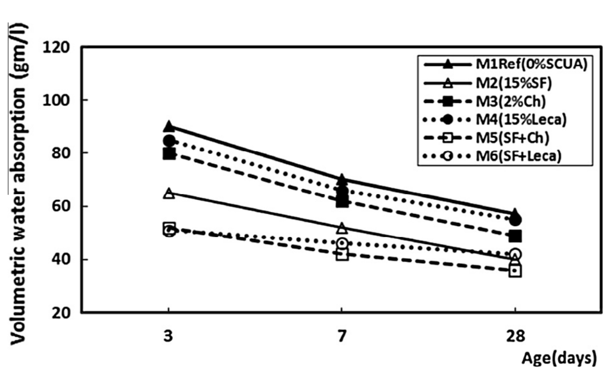

Figure 5 Effect of self-curing agent type on volumetric water absorption of concrete (air-curing at 25 °C).

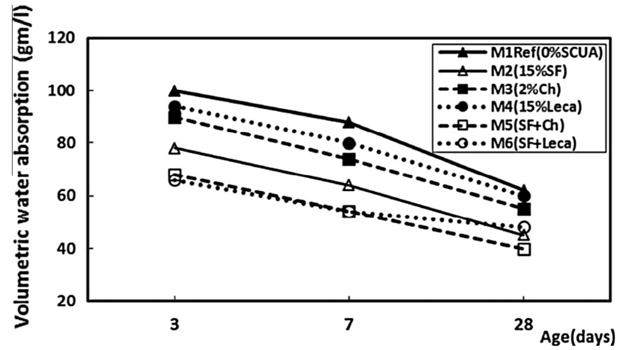

Figure 6 Effect of self-curing agent type on volumetric water absorption of concrete (air-curing at 50 °C).

4.4. Mass loss

It can be seen from the test results that, the mass loss of all self-curing and conventional concretes increased gradually with time under air curing due to water evaporation from concrete as shown in Fig. 7. The presence of silica fume and self-curing agents in concretes caused an additional reduction in mass loss relative to conventional concrete during the experiment to confirm that a better water retention occurred. The concretes containing 15% SF or 2% Ch showed better performance and insured 22.6% and 19.4% reduction in mass loss, respectively, compared to the reference concrete.

The mass loss of all studied concretes significantly increased with time when exposed to high temperature due to high water evaporation as shown in Fig. 8. The incorporation of

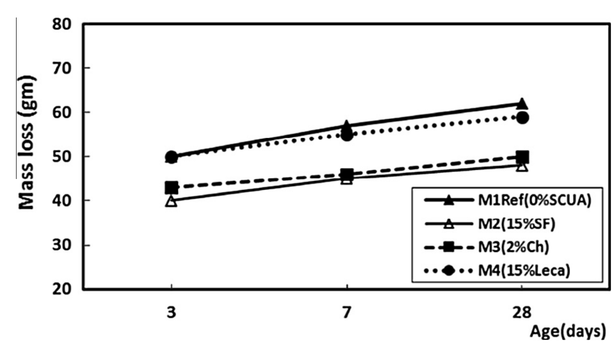

Figure 7 Effect of self-curing agent type on mass loss of concrete (air-curing at 25 °C).

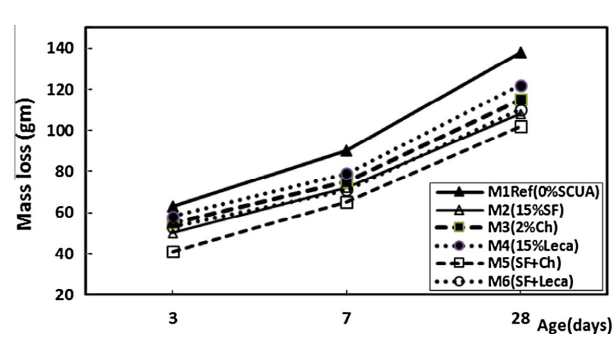

Figure 8 Effect of self-curing agent type on mass loss of concrete (air curing at 50 °C).

self-curing agents in concrete mixtures caused a significant reduction in mass loss relative to conventional concrete during the experiment. This reduction was 20.3%, for concretes of 15% silica fume and 15% SF + Leca, while was 26.1% for concrete with 15% SF + 2% Ch at 28 days.

A comparison between the mass losses of all concrete mixes cured in elevated relative to normal temperature can be seen in Table 4.

5. Durability

5.1. Carbon dioxide attack

5.1.1. Compressive strength

Figs. 9 and 10 present the compressive strength at different ages up to 6 months for concrete mixes with and without SCUA cured in air and exposed to 5% CO_2. As shown in Fig. 9 the compressive strength systematically increases with time and with the use of silica fume and self-curing agent in concrete, compared with reference concrete. Concretes with silica fume showed significant higher in strength during the experiment, the concrete contained SF + Ch (M5) ensured the highest increase by about 60.5% compared with reference concrete at 6 months age.

In the concrete series exposed to 5% CO_2, the compressive strength of all concrete mixes (self-curing and conventional concretes) increased gradually with time and approximately showed similar trend up to 6 months as shown in Fig. 10. The incorporation of SF into concrete without and with SCUA recorded a max improvement in the compressive

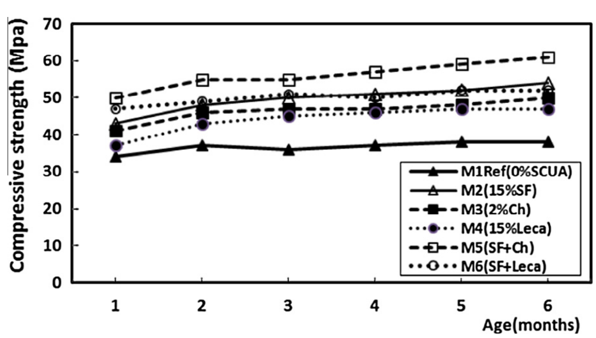

Figure 9 Effect of self-curing agent type on compressive strength of concrete (cured in air).

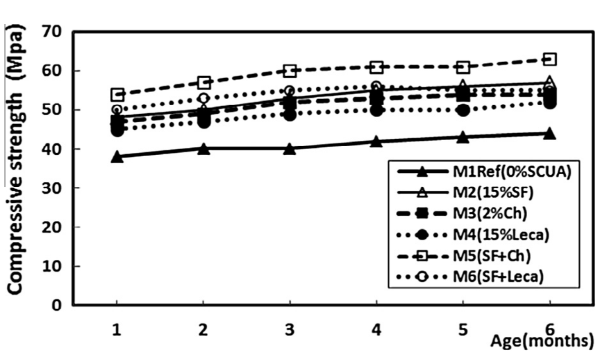

Figure 10 Effect of self-curing agent type on compressive strength of concrete (cured in 5% CO_2).

strength. This improvement was 27.3%, 43.2 and 25% after 6 months exposure for concretes containing SF only (M2), SF + Ch (M5) and SF + Leca (M6), respectively, compared with reference concrete (M1Ref.), Table 5.

The test results indicate that, the diffusion of carbon dioxide into concrete improved the compressive strength which may be attributed to pore filling process with calcium carbonate product [21], therefore higher porosity concrete was more affected as indicated in Table 5. After 6 months, the enhancement in compressive strength was the highest for reference and self-curing concretes with 15% leca by about 15.8% and 10.6%, respectively, when exposed to 5% CO_2 compared with similar concretes cured in air.

5.1.2. Ph value

The incorporation of silica fume into concrete mixture caused a reduction in the Ph value, 16.3% decrease compared with conventional concrete, which may be attributed to the conversion of the calcium hydroxide which is responsible for increasing the Ph value into calcium silicate hydrate (C-S-H) as shown in Fig. 11. The Ph values of all studied concretes without silica fume (self-curing with ch or leca and conventional concretes) increased gradually with time due to the production of calcium hydroxide as a result of continuation of cement hydration and ensured higher values compared to their corresponding concretes with SF after 6 months, Table 5.

Fig. 12 illustrates the variation in the Ph values of the concrete mixes studied due to the exposure to 5% CO_2 for 6 months. All the mixes exhibit a continuous reduction in the Ph value with different rates according to the concrete type (CO_2 diffused in concrete and react with calcium hydroxide – basic – which reduce the Ph value of concrete). The concrete with silica fume only or along with Ch showed the lowest variation in Ph value and was around constant, due to less porosity which restrict CO_2 diffusion.

Comparing the results of Ph values of concretes cured in air and corresponding concretes exposed to 5% CO_2 for 6 months indicates higher reduction of, 20%, 18%, and 16% for concrete with Ch, leca and the reference, respectively, while concrete with SF (M2) the variation was almost nil, Table 5.

5.2. Sodium chloride attack

5.2.1. Compressive strength

For the concrete series cured in sodium chloride solution (8%), the compressive strength increased with time up to 4 or continued to 5 months for concrete with SF or with SF + Ch, respectively, while for non-silica fume concretes the time was limited to 3 months, beyond that the strengths started to decrease until the end of the 6 months test period as shown in Fig. 13. Self-curing concretes exhibited higher increase in strength (f_{cu}) during the experiment compared with the reference concrete which may be attributed to the continuation of the hydration process. Additional increase in f_{cu} produced in the case of concretes with silica fume due to production of C-S-H (calcium silicate hydrate), which leads to less voids, less pores, and greater bond force between the cement paste and aggregate thus reducing the penetration of sodium chloride solution into concrete [22]. However in the reference concrete, the porosity of concrete is relatively high and allows sodium chloride solution to penetrate into the concrete pores and

Table 5 Effect of carbon dioxide attack on compressive strength and ph values after 6 months exposure.

Concrete mix	Considered property									
	Compressive strength, f_{cu} (MPa)					Ph values				
	Air curing	Vari.[a] %	5% CO_2 curing	Vari.[b] %	Vari.[c] %	Air curing	Vari.[a] %	5% CO_2 curing	Vari.[b] %	Vari.[c] %
M1 (Ref.)	38	0.0	44	0.0	+15.8	12.51	0.0	10.55	0.0	−16
M2 (15% SF.)	54	+42.1	56	+27.3	+3.7	10.48	−16.2	10.50	−0.47	+0.2
M3 (2% Ch.)	50	+31.6	54	+22.7	+8.0	12.93	+3.4	10.45	−0.95	−20
M4 (15% leca)	47	+23.7	52	+18.2	+10.6	12.90	+3.1	10.64	+0.85	−18
M5 (SF + Ch)	61	+60.5	63	+43.2	+3.3	10.75	−14.1	10.33	−2.08	−3.9
M6 (SF + Leca)	52	+36.8	55	+25.0	+5.7	10.84	−13.34	10.12	−4.08	−6.6

[a] The variation in the values of the considered property (at air curing) compared to the value of M1 (Ref.).
[b] The variation in the values of the considered property (at 5% CO_2 curing) compared to the value of M1 (Ref.).
[c] The variation in the values of the considered property at 5% CO_2 curing compared to the values at air curing.

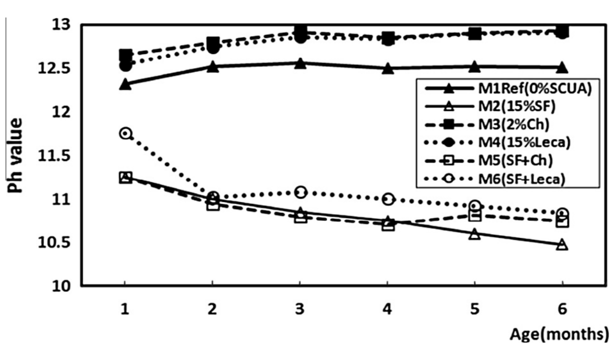

Figure 11 Effect of self-curing agent type on Ph values of concrete (cured in 8% air).

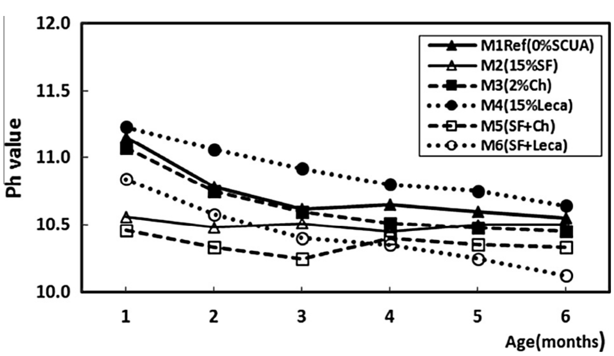

Figure 12 Effect of self-curing agent type on Ph values of concrete (cured in 5% CO_2).

chloride salts crystallize (due to alternation of wetting and drying action in NaCl solution) within the pores inducing internal cracks, which badly affect the compressive strength. In general, after 6 months exposure to 8% NaCl, concrete with 15% silica fume, self-curing concretes with 2% Ch and 15% leca gave higher compressive strength by about 67.7%, 48.4% and 35.5%, respectively, compared with 0.0% SCUA (conventional concrete). Adding 15% SF to SCUC with 2% Ch or with 15% Leca (M5, M6) ensured 28.3%, 19.1% increase in f_{cu}, respectively, compared to their corresponding concretes without SF (M3, M4).

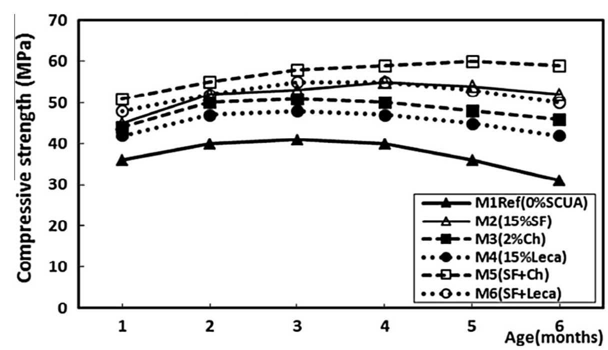

Figure 13 Effect of self-curing agent type on compressive strength of concrete (cured in 8% sodium chloride solution).

When concretes immersed in 8% sodium chloride solution, the solution diffused in concrete and reduced the compressive strengths compared with concretes cured in air (Fig. 9) as indicated in (Table 6). Generally, chloride solution attack reduced the compressive strength of the studied concretes; higher reduction took place with the reference and self-curing concrete with 15% Leca by about 18.5% and 10.6%, respectively, at 6 months exposure compared with concretes in air, due to the higher porosity in comparison with the other investigated concretes.

5.2.2. Tensile strength

Fig. 14 indicates that, the tensile strength of all concrete mixes (self-curing and conventional concretes) increased with time under air curing (25 °C). The tensile strength increases with the use of self-curing agent in concretes. Silica fume concrete showed higher strength during the experiment followed by Ch concrete, leca concrete and conventional concrete. At the age of 6 months concretes with 15% silica fume, self-curing agents 2% Ch and 15% leca gave higher tensile strength by about 39.6%, 34.8% and 18%, respectively, compared with the conventional concrete.

For the concrete series cured in sodium chloride solution (8%), tensile strength increased with time up to 6 months for silica fume concrete and concrete with SF + Ch while in case of non-silica fume concretes (Ch, leca and conventional concretes) the increase was within period of 5, 4 and 3 months,

Table 6 Effect of wet/dry cycles in saline water (8% sodium chloride) on different concrete properties after 6 months.

Concrete mix	Considered property											
	Compressive strength (MPa)			Tensile strength (MPa)			V.W.A. (g/L)			Mass loss (g)		
	Air curing	Wet/dry cycles (8% sodium chloride)	Variation %	Air curing	Wet/dry cycles (8% sodium chloride)	Variation %	Air curing	Wet/dry cycles (8% sodium chloride)	Variation %	Air curing	Wet/dry cycles (8% sodium chloride)	Variation %
M1 (Ref.)	38	31	−18.4	2.73	2.00	−26.7	40	21	−47.5	81	63	−22.2
M2 (15% SF.)	54	52	−3.7	3.81	3.71	−2.6	25	10	−60.0	57	54	−5.3
M3 (2% Ch)	50	46	−8.0	3.68	3.40	−7.6	31	12	−61.3	63	57	−9.5
M4 (15% leca)	47	42	−10.6	3.22	3.02	−6.2	38	17	−55.0	76	67	−11.8
M5 (SF + Ch)	61	59	−3.3	–	4.06	–	–	7.5	–	–	51	–
M6 (SF + Leca)	52	50	−4.0	–	3.62	–	–	15	–	–	61	–

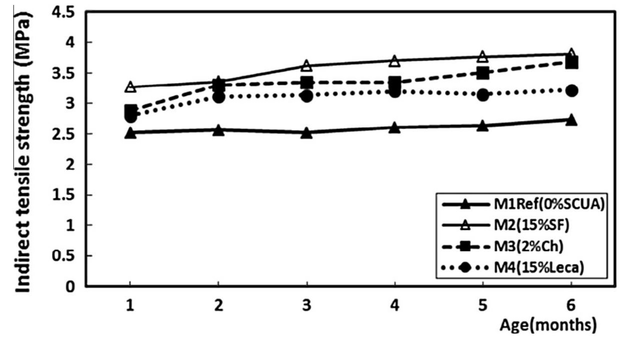

Figure 14 Effect of self-curing agent type on indirect tensile strength of concrete (cured in air).

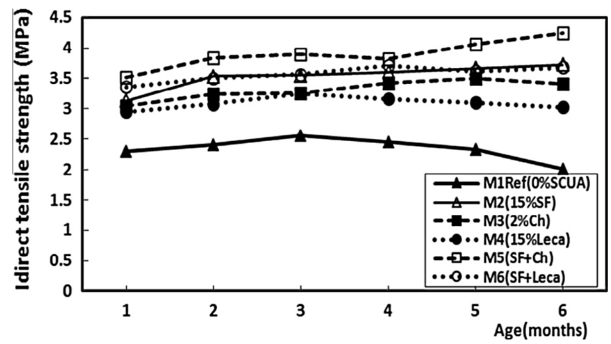

Figure 15 Effect of self-curing agent type on indirect tensile strength of concrete (cured in 8% sodium chloride solution).

respectively, beyond that strengths started to decrease until the end of the 6 months test period as shown in Fig. 15. Silica fume and self-curing concretes exhibited higher strength during the experiment compared with the reference concrete. In general, after 6 months exposure, self-curing concretes with 15% silica fume (M2), or SF + 2% Ch gave the highest improvement in tensile strength by about 86%, 100%, respectively, compared with the conventional concrete.

Chloride solution attack reduced the tensile strength of the reference and self-curing concretes, the lowest reduction was with 15% silica fume and 2% Ch concretes at 6 months compared with their corresponding concretes in air as shown in Table 6.

5.2.3. Volumetric water absorption

Fig. 16 reveals that the volumetric water absorption (VWA) of all concrete mixes decreased gradually with time under air curing. Volumetric water absorption systematically decreases when self-curing agents of Ch type or silica fume (SF) used in concrete, which point to a better water retention, causing more hydration of cement [3,17–19], which leads to less porous and more compact concrete than conventional concrete. On the other hand, the leca type gave higher values in VWA than conventional concrete may be due to higher porosity of leca particle. After 6 months, self-curing concretes with 15% silica fume, 2% Ch and 15% leca gave variation in volumetric water absorption by about −37.5%, −22.5% and −5.0%, respectively, compared with 0.0% SCUA (conventional concrete).

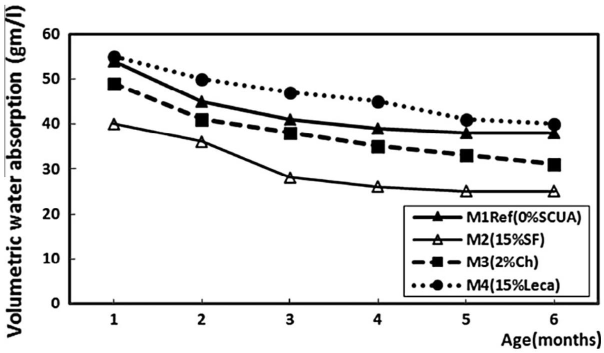

Figure 16 Effect of self-curing agent type on volumetric water absorption of concrete (cured in air).

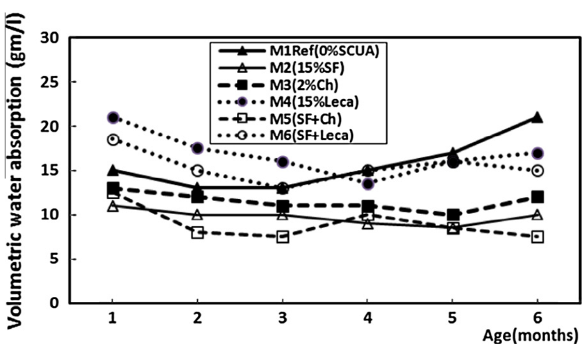

Figure 17 Effect of self-curing agent type on volumetric water absorption of concrete (cured in 8% sodium chloride).

The VWA of the concretes cured in 8% sodium chloride solution (Fig. 17) decreased gradually up to certain age then started to increase again according to the SCUA type. At early ages, concrete with leca showed high VWA compared with conventional concrete for up to 3 months, beyond that the VWA was decreased; however, concretes with SF, Ch type and SF + Ch gave less values of VWA compared with conventional concrete during the experiment. At later ages, the addition of self-curing agents into concrete mixtures without or with SF caused better water retention capacity in concrete and thereby producing less porosity concrete due to the continuity of the hydration process, which appeared in the reduction of VWA compared to conventional concrete. After 6 months exposure the self-curing concretes with 15% silica fume, 2% Ch and SF + Ch gave lower volumetric water absorption by about 52.4%, 42.9% and 64.3%, respectively, compared with conventional concrete.

The chloride solution attack, with concentration (8%), in concretes caused a reduction in VWA compared with their corresponding concretes cured in air after 6 months which may be attributed to the pore filling process by salt ions as shown in Table 6.

5.2.4. Mass loss

It can be seen from the test results shown in Fig. 18 that the mass loss of all concrete mixes studied increased gradually with time under air curing due to water evaporation from concrete. The use of self-curing agents in concretes caused a reduction in the mass loss particularly the use of Ch. or silica fume relative

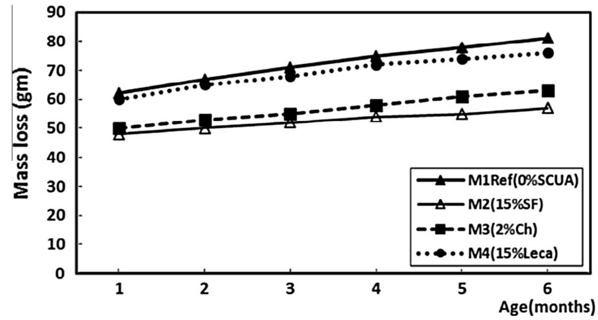

Figure 18 Effect of self-curing agent type on mass loss of (concrete cured in air).

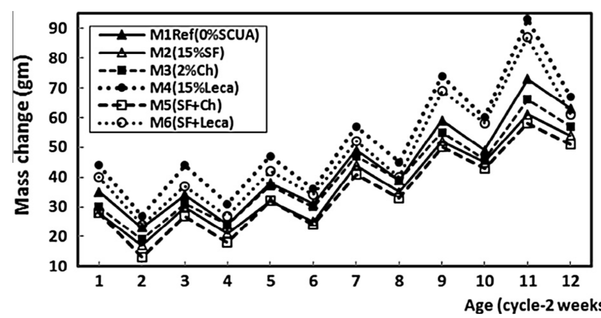

Figure 19 Effect of self-curing agent type on mass change of chloride in concrete (cured in 8% sodium chloride).

to conventional concrete during the experiment, which confirms that a better water retention occurred in such concretes. At 6 months, the concrete with 15% silica fume and self-curing concretes with 2% Ch and 15% leca gave lower mass loss by about 29.6%, 22.2% and 6.2%, respectively, compared with conventional concrete.

Fig. 19 shows the mass change of the concretes studied exposed to wetting and drying cycles in 8% sodium chloride solution. The results revealed that the mass of all concrete mixes (self-curing and conventional concretes) decreased at dry cycles (2 weeks) due to evaporation of water and increased at wet cycles (2 weeks) due to partially saturation by solution. Mass change decreases when self-curing agent Ch type or SF used in concrete relative to the reference concrete. On the other hand, leca type incorporated into concrete gave higher values of mass change than conventional concrete, which may be correlated to the higher porosity of leca particle. At the end of the test period of dry cycles, self-curing concretes with 15% silica fume, 2% Ch and 15% leca had variation in mass by about −14.3%, −9.5% and +6.4%, respectively, compared with 0.0% SCUA (conventional concrete).

The addition of SF to the SCUC either with Ch or Leca type had a significant effect in reducing the mass loss, by about 19%, 3.2% compared to conventional concrete and by 10.5%, 9% relative to corresponding concretes without SF (M3, M4), respectively.

Generally, the mass loss of concretes exposed to wet/dry cycles in 8% chloride solution increased compared with similar concretes cured in air, the lowest variation recorded for concretes with SF and Ch, at the end of 6 months (−5.3%, −9.5%), Table 6.

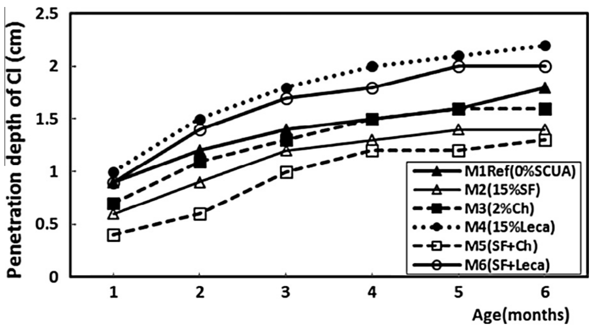

Figure 20 Effect of self-curing agent type on penetration depth of chloride in concrete (cured in 8% sodium chloride).

5.2.5. Penetration depth of chloride

Fig. 20 shows the penetration depth in concretes immersed in saline water versus time. It is obviously that, the penetration depth values increased gradually with time for all concretes. Concrete of (Leca type) was higher affected specially the mix without silica fume (M4) due to higher porosity of leca particles where the penetration depth increased by about 22% while 11% for concrete of Leca + SF relative to the conventional concrete (C.C) at 6 months. Using poly-ethylene glycol as self-curing agent in concrete reduced the penetration depth due to more water retention produced more hydration and lower porosity which gave lowered values by about 11% relative to conventional concrete after 6 months exposure. Incorporation of silica fume in concretes lowered penetration depth by about 22% in case of concrete without self-curing agents (C.C), 19% in case of SCUC with Ch. type and 9% in case of SCUC with Leca type at 6 months compared with the corresponding concretes without SF.

6. Conclusions

The experimental results previously discussed lead to the following conclusions:

1. The use of 15% silica fume and self-curing agents (2% poly-ethylene-glycol or 15% saturated leca) separately or in conjunction in concrete mixes improves all properties of concretes under all curing regimes which may be attributed to a better water retention results in lower voids and pores thereby greater bond force between the cement paste and aggregate is produced compared to conventional concrete.
2. The results have indicated the superior performance of concrete containing 15% silica fume in different curing regimes; in air (25 °C, 50 °C), in 5% CO_2, wet and dry cycles in 8% NaCl solution. The concrete resulted in the highest increase in the compressive and the tensile strength as well as the highest reduction in the volumetric water absorption and the mass loss compared to the concretes with poly-ethylene glycol and saturated leca, so it should be considered as one of the best agents for the self-curing concrete (SCUC).
3. The incorporation of silica fume as a pozzolanic self-curing admixture in concrete perfectly improves all concrete properties not only due to pozzolanic reaction but also due to its ability to retain water – appeared in the significant reduction of VWA and mass loss; (29.8 and 27.4) and (22.6% and 20.3%) at 28 days for concrete cured in air at (25 °C and 50 °C), respectively, in comparison with the conventional concrete, which causes continuation of the cement hydration resulted in concrete densification with small, less, and discontinuous pores.
4. Elevated temperature (50 °C) enhanced the compressive and the tensile strength values of self-curing concretes during the test period of 6 months, which may be correlated to the acceleration of cement hydration due to the availability of retained water in such concretes; in contrast, it had an adverse effect on conventional concrete (a continuous reduction in strength during the test period).
5. The addition of silica fume into concrete mixtures caused a reduction in the Ph value which may be attributed to the conversion of the calcium hydroxide which is responsible for increasing the Ph value to calcium silicate hydrate (C-S-H). However the variation in the Ph value was insignificant in the case of the concretes with silica fume and in conjunction with poly-ethylene glycol, exposed to 5% CO_2 for 6 months.
6. The conventional concrete and the self-curing concretes (with SF, Ch, and leca) exposed to 5% CO_2, improved in the compressive strength during the exposure period (6 months) due to pore filling process by carbon ions. The concrete with higher porosity exhibited higher increase in the compressive strength, 15.8%, (3.7%, 8%, and 10.6%) increase for conventional, SCUC (with SF, Ch, and leca), respectively, compared with the corresponding concrete cured in air after 6 months (Table 5).
7. Exposing the investigated concrete to wet/dry cycles of saline water (8% NaCl), reveled initially a gradual increase in the compressive and the tensile strength then followed by retrogression in strength in different degrees and times. The compressive strength and the tensile strength of conventional concrete were reduced by (18.4% and 26.7%), respectively. However the self-curing concretes exhibited less reduction (3.7%, 8%, and 10.6%) in the compressive strength and (2.6%, 7.6%, and 6.2%) in the tensile strength of concretes with SF, Ch, and leca, respectively, compared to the corresponding concretes cured in air (Table 6).
8. Generally, a significant improvement in all considered concrete properties due to the addition of 15% SF along with self-curing agents has been achieved, especially with 2% of Polyethylene-glycol (Ch) which absolutely ensured the best results and good durability properties in all curing regimes (hot weather – 50 °C, 5% CO_2, wet/dry cycles in 8% NaCl).

Acknowledgment

The authors gratefully acknowledge the support provided by the Department of Civil Engineering, Structural engineering, at El-Mansoura University in particular, as well as the concrete and material laboratories to carry out this work. Moreover, the author greatly thanks to prof. Dr. SalahEl-Metwally for his assistance in proof reading the paper.

References

[1] D.P. Benz, K.A. Snyder, Protected paste volume in concrete extension to internal curing using saturated light weight fine aggregate, Cem. Concr. Res. 29 (1999) 1863–1867.

[2] M. Geiker, D.P. Bentz, O.M. Jensen, Mitigating autogenous shrinkage by internal curing in high-performance structural lightweight concrete, Am. Concr. Inst. 218 (2004) 143–154.
[3] M.J. Ole, L. Pietro, Techniques and materials for internal water curing of concrete, Mater. Struct. 39 (2006) 817–825.
[4] D.P. Bentz, Influence of internal curing using lightweight aggregates on interfacial transition zone percolation and chloride ingress in mortars, Cem. Concr. Compos. 31 (2009), 285–289.
[5] S. Ghourchian, M. Wyrzykowski, P. Lura, M. Shekarchi, B. Ahmadi, An investigation on the use of zeolite aggregates for internal curing of concrete, Constr. Build. Mater. 40 (2013) 135–144.
[6] j. Castro, L. Keiser, M. Golias, J. Weiss, Absorption and desorption properties of fine lightweight aggregate for application to internally cured concrete mixtures, Cement Concr. Compos. 33 (2011) 1001–1008.
[7] M.V. Jagannadha Kumar, M. Srikanth, K. Jagannadth Rao, Strength characteristics of self-curing concrete, IJRET 1 (2012) 51–57.
[8] D.P. Bentz, P. Lura, J.W. Roberts, Mixture proportioning for internal curing, Concr. Int. 27 (2005) 35–40.
[9] S. Zhutovsky, K. Kovler, Effect of internal curing on durability-related properties of high performance concrete, Cem. Concr. Res. 42 (2012) 20–26.
[10] R. Troli, A. Borsoi, S. Collepardi, G. Fazio, M. Collepardi, S. Monosi, Self-compaction/curing/compressing concrete, in: 6th International Congress, Global Construction, Ultimate Concrete Opportunities, Dundee, UK, 5–7 July, 2005.
[11] A.S. El-Dieb, Self-curing concrete: water retention, hydration and moisture transport, Constr. Build. Mater. 21 (2007) 1282–1287.
[12] B. Mather, Self-curing concrete, Why not?, Concr Int. 23 (1) (2001) 46–47.
[13] S. Wrber, H.W. Reinhardi, Various curing method applied to high-performance concrete with natural and blended aggregates, in: Proceedings of Fourth International Symposium on the Utilization of high Strength/High Performance concrete, Paris, May 29–3, vol. 3, 1996, pp. 1295–1303.
[14] M.D. Cohen, B. Mather, Sulphate attack on concrete – research needs, ACI Mater. J. 88 (1991) 62–68.
[15] R.F. Feldman, C.Y. Huang, Properties of Portland cement-silica fume pasts 1, porosity of surface properties, Cem. Concr. Res. 15 (1985) 765–774.
[16] D. Cusson, T.J. Hoogeveen, L.D. Mitchell, Internally-cured high-performance concrete under restrained shrinkage and creep, in: 7th International Symposium on utilization of High-Strength/High Performance Concrete, Nates, France, 12–14 September, 2005, pp. 579–584.
[17] D.P. Bentz, O.M. Jensen, Mitigation strategies for autogenously shrinkage cracking, Cement Concr. Compos. 26 (2004) 677–685.
[18] O.M. Jensen, P.F. Hansen, Water-entrained cement-based materials I. Principle and theoretical background, Cem. Concr. Res. 31 (2001) 647–654.
[19] B.S.M. Persson, Self-desiccating high-strength concrete slabs, in: Proceedings Utilization of High Strength Concrete, Symposium in Lillehammer, Norway, June 20–23, 1993, pp. 882–889.
[20] T.A. Hammer, The maturation of mechanical properties of high strength concrete exposed to different moisture conditions, in: Proceedings Third international Symposium on Utilization of High-Strength Concrete, Lillehammer, Norway, vol. 2, June 20–24, 1993, pp. 1084–1091.
[21] J. Gajda, Absorption of atmospheric carbon dioxide by Portland cement concrete, PCA R&D Serial No. 2255a, vol. 43, Portland cement Association, Skokie, lllinois, 2001.
[22] A.Z. Yehia, Application of Self-curing Concrete in Egypt, Ph.D Thesis, Structural Engineering Department, Mansoura University, Egypt, 2010.